UNIVERSITY OF CALIFORNIA

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Exploring the Role of Electrification in Green Ridesourcing

A thesis submitted in partial satisfaction of the requirements for the degree

Master of Urban and Regional Planning

by

Jiawen Fang

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ABSTRACT OF THE THESIS

Exploring the Role of Electrification in Green Ridesourcing

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Master of Urban and Regional Planning

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The rapid growth of ridesourcing services, provided by Transportation Network Companies (TNCs) like Uber and Lyft, has uncertain environmental impacts. Although the ridesourcing services can potentially reduce the environmental costs of single occupancy driving (SOV) over the "life cycle" of auto ownership and use, including emissions from driving, auto manufacturing, end-of-life disposal, and infrastructure (roads and parking), it can also increase travel by reducing its cost. This research analyzes and compares different SOV and TNC travel scenarios using a conceptual model applied to travel behavior data from the city of San Francisco. The results show that: (1) There exists a "green point" ranging from 5 to 40 percent, which is the level of induced trips that makes TNC emissions exceed SOV emissions; (2) Hybrid and electric vehicles contribute to emissions reduction across all scenarios. Higher fuel economy and cleaner energy can

not only help reduce greenhouse gas emissions when there are no induced trips, but also slow GHG emission growth as the level of induced trips goes up; (3) Hybrid vehicles appear a more cost-effective alternative to electric vehicles for reducing pollution; (4) Vehicle cost and the spread between gasoline and electricity price are critical factors influencing the cost-effectiveness of electric vehicles; (5) States with a clean electric grid and high spread between gasoline and electricity prices (e.g. California, Washington) are the best candidates for electrification of private vehicles and TNC fleets.

The thesis of Jiawen Fang is approved.

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1 Introduction

The recent emergence of app-based, on-demand ride services has sparked great debate over their role in urban transport. We refer to these services—provided by Transportation Network Companies (TNCs) like Uber and Lyft— as "ridesourcing." Ridesourcing dynamically matches supply and demand by allowing travelers to request car rides in real-time from potential suppliers using a smartphone application (Rayle, Shaheen, Chan, Dai, & Cervero, 2014). Ridesourcing terminology is inconsistently defined by the transportation sector, like the misused word "ride-sharing" when referring to ridesourcing companies (Goddin, 2014). These two terms are different in the following ways: (1) Ridesharing is where a driver and passenger share a common origin-destination by way of carpooling or vanpooling, while in ridesourcing, drivers and passengers do not share a common origin-destination; (2) The drivers of ridesharing is usually not profit motivated, while ridesourcing drivers have for-profit motivation; and (3) Ridesharing is focused on filling empty seats with a goal of reducing travel costs, congestion and fuel consumption, all of which might be increased by ridesourcing due to pick-up deadheading (Ngo, 2015).

Some other names including "Transportation Network Companies (TNCs)", "ride-hauling" ,"ride-booking" ,"ride-matching" ,"on-demand rides" ,and "app-based rides" also refer to ridesourcing services. For consistency with the literature, this research uses the term "ridesourcing" because it conveys the essential technology—a platform used to "source" rides from a driver pool (Rayle, Dai, Chan, Cervero, & Shaheen, 2016). Thus, ridesourcing can be stated as the sourcing of rides from a for-fare driver pool accessible through an app-based platform (Henao & Marshall, 2017).

The use of ridesourcing services is growing rapidly. A recent national poll (Morning Counsult, 2015) suggested that ridesourcing use was roughly comparable to use of taxis (3% of respondents reporting "almost daily" use of both modes). As of the summer 2016, Uber was operating in 450 cities globally and had completed two billion trips, with first billion completed in its first six years of operation and the second one billion completed in the succeeding six months (Somerville, 2016). Uber's estimated valuation continues to grow and currently is at $63 billion, without owning any vehicle fleet, associated vehicle infrastructure, and few employees, as the drivers are classified as independent contractors. The smaller, but still large, Lyft operated exclusively in the U.S. in 2016 and was valued at about $5.5 billion (Solomon, 2016).

The rapid growth of ridesourcing services has raised both hopes and fears among public officials, transportation planners and analysts, and environmentalists for their future role in cities, both in the U.S. and elsewhere. As a new transportation option, ridesourcing typically offers a higher level of availability, reliability, and ease-of-use than traditional taxi and public transit services, without the cost and inconvenience of parking. But the rise of ridesourcing services has also raised concerns about their effects on traffic congestion and vehicle emissions (Schaller, 2017). Although the ridesourcing services provide substitutes for privately owned vehicles and, in turn, single-occupant driving, parking, and manufacturing, their ease and low cost might also generate additional trips by customers, as well as "deadheading" when drivers move between drop-offs and pickups. People may make more trips thanks to the increasing convenience of ridesourcing services. Our limited experience with these new and evolving services, and lack of publicly available data on their use make it difficult to reliably estimate their environmental effects. It is even unclear as to under what conditions ridesourcing services can be expected to reduce or increase the environmental impacts, a gap this research aims to address.

Given this gap in our understanding of the environmental effects of ridesourcing, the analysis reported here examines two questions: (1) Under what conditions can ridesourcing services reduce environmental impacts compared to single occupancy driving? (2) How might hybrid and electric vehicles help reduce the environmental impacts of ridesourcing services? To answer the first question, I assessed and compared the operational environmental impacts of conventional single occupancy driving (SOV) and ridesourcing services (TNC). The discussion was focused on greenhouse gas emissions (GHG) and calculated in units per vehicle miles traveled (VMT). I selected San Francisco as the sample city based on the availability of the travel behavior data. To address the second question, I calculated the additional costs and potential GHG reduction of shifting from gasoline to hybrid or electric vehicles in the ridesourcing sector for each state in the U.S. using the same travel behavior data with San Francisco. I then conduced a spatial analysis to identify the potential benefits of electrification of TNC, and more generally, light-duty auto fleet by state.

In this research, I exploit two different tools cum datasets. The first is the Alternative Fuel Lifecycle Environmental and Economic Transportation (AFLEET) Tool[1], which is used for

[1] https://greet.es.anl.gov/afleet_tool

calculating life cycle environmental impacts of vehicle operation and fuel production. The second source of data is travel behavior dataset for San Francisco, which shows how trip lengths were broken down by speed[1]. The environmental impacts of vehicle operation are affected by fuel economy, which is initially determined by the running speed. I broke ridesourcing trips down into *high speed in-service trips* (driving with passengers) and *low speed out-of-service trips* (cruising to waiting for requests and picking up passengers). San Francisco Transportation Authority provided me with the dataset that included the average length of in-service trips and out-of-service trips by hour. For single-occupancy driving, the trips were divided into *high speeding driving* and *low speed cruising for a parking space*.

I aim to contribute to both scholarship and policymaking through this research. Leveraging the previous studies on transportation lifecycle environmental impacts assessment (Transportation LCA) and current travel behavior data, this is the first study to consider out-of-service trips in assessing the environmental impacts of ridesourcing services. The results should be useful reference for policymakers to incorporate shared mobility into current transportation system. Ridesourcing service providers may also be better able to assess their contribution to the sustainability and improve their operating efficiency as well.

[1] https://www.sfcta.org/tncstoday

2 Literature Review

Current research on ridesourcing services focuses more on the characteristics of users, trip purposes, and impacts on travel behaviors, usually based on survey data aggregated to the city, regional, or national level. Bivariate and multivariate logit models are typically used to analyze the influencing factors of mode choice. However, the overall environmental impacts in these studies are unclear due to the lack of both clear travel behavior/mode choice conceptual models and disaggregated travel behavior data. On the one hand, ridesourcing services can reduce car dependence and parking demands. On the other hand, they might increase emissions due to ridesourcing services encouraging new trip making, ridesourcing drivers' cruising for customers, and increased traffic congestion due to the added ridesourcing travel.

2.1 The Characteristics of Ridesourcing Users and Trips

There is little academic literature on ridesourcing due to the lack of open data on these services. As for the demographic characteristics of ridesourcing users, several studies have found that ridesourcing users tend to be young, well-educated, high-income, own fewer cars, and frequently traveling with companions (Dias, et al., 2017). A nation-wide survey also showed that men tend to use ridesourcing services more than women (Dawes, 2016). Survey data on business travelers' use of ridesourcing indicate that they select ridesourcing more frequently than taxis (Certify, 2017). Ridesourcing services also tend to be used more frequently in high population density cities where wait times tend to be lower for both drivers and passengers.

In terms of trip purpose, ridesourcing appears to offer a functional alternative for driving to work, but mostly as a supplement to regular commute trips; they are also commonly used as an alternative to unsafe or inconvenient driving (such as from a bar and/or late at night), as well as trips to and from airports (Dawes, 2016). Finally, ridesourcing services tend to be used more frequently for social and recreation trips than for work trips (Murphy, 2016).

2.2 Comparative Studies on Taxi Services

With characteristics similar to taxis, but also the potential to realize some of the benefits of both taxis and ridesharing, ridesourcing has become the most direct competitor of the taxi industry and received significant criticism from taxi interests, who have often characterized ridesourcing as an illegal activity that flouts existing laws and competes unfairly. On the one hand, ridesourcing has enabled more efficient use of vehicles that drivers already own. On the other, ridesourcing's apparent efficiency advantages may also be explained in part by its exemption from the supply restrictions that often govern taxis (Rayle, Dai, Chan, Cervero, & Shaheen, 2016). Despite their small modal share, taxis have been shown to fill the gap when driving or other public transit modes were not available (Gilbert & Samuels, 1982; Wohl, 1975). Similarly, taxis have been shown to be both complements and substitutes for public transit (Austin & Zegras, 2012). Shared taxis could potentially bring benefits, including increased efficiency, lower costs for passengers and reduced congestion and overall vehicle travel (Enoch, Potter, Parkhurst, & Smith, 2004; Sant, et al., 2014), though most cities in the U.S. have prohibited unrelated passengers from sharing a taxi. Lack of information, among both passengers and drivers, has long plagued taxi markets – riders generally cannot compare information on price or service quality before choosing a vehicle, which often resulted in poor service quality. Absent regulation, low barriers to entry in taxi markets tended to encourage over competition, aggressive driver behavior, poor vehicle maintenance, and congestion (Schaller, 2007).

Both taxi and ridesourcing should have additive and subtractive effects on overall vehicle miles traveled (VMT) by providing increased access to door-to-door transportation and by discouraging vehicle ownership (Anderson D. N., 2004); but the much older taxi services were primarily additive and regulated with the goal, among others, to equalize access to taxis across users and neighborhoods (Cooper & Mundy, 2010). Scholars who have modelled taxi systems have focused on the relationships between taxi supply, demand, pricing, and efficiency (George, 1972; Guri, 2005). Taxicab efficiency can be calculated in terms of time or distance and measured as the ratio of paid time or mileage for which a taxicab is occupied by a passenger to the unpaid time spent, or miles driven without a passenger (Arnott, 1996). Regulators had an interest in promoting taxi efficiency, not only because inefficient taxi miles contribute to pollution and congestion, but also because a more efficient system permitted lower regulated taxi fares (Anderson D. N., 2014). The concept of a spatial-temporal strategy, which referred to the spatial and temporal choices drivers made to increase and avoid danger, was suggested in ethnographic studies of taxicab drivers (Anderson D. N., 2004; Davis, 1990).

2.3 The Behavioral Impacts of Ridesourcing

Only very recently have reports emerged that featured the potential travel behavioral impacts of ridesourcing services. On the one hand, studies have suggested that ridesourcing services could reduce the demand for driving and parking. A national survey conducted in 2016 (Shared-Use Mobility Center, 2016) found that ridesourcing trips substituted for trips by car-sharing (24%) and driving alone (20%). Another survey in Austin indicated that 9 percent of ridesourcing users would buy a new car if such services pulled out (Hampshire, Simek, Fabusuyi, Di, & Chen, 2017). Users in Pittsburg also suggested that they would have driven their own cars if there were no ridesourcing services (Chen, 2015). People who used more shared modes were more likely to ride public transit and own fewer vehicles (Shared-Use Mobility Center, 2016; Pew Research Center, 2016). On the other hand, a recent national survey showed that there was no strong correlation between ridesourcing use and vehicle ownership, and 91 percent of the ridesourcing users had not made any changes to vehicle ownership (Clewlow & Kulieke, 2017). This report also found that ridesourcing services resulted in a 6 percent reduction in transit use among people who changed their behavior after using ridesourcing services. One study in San Francisco (Rayle, Shaheen, Chan, Dai, & Cervero, 2014) concluded that ridesourcing both substituted and complemented public transit, walking, and biking. In sum, the effects of ridesourcing on travel behavior generally, and vehicle travel in particular are uncertain and likely still evolving.

2.4 The Environmental Impacts of Ridesourcing

Ridesourcing services could reduce car dependence and encourage sharing rides, with the options of Uber Pool and Lyft Line. While not specific to ridesourcing alone, one report estimated that using information and communications technologies to optimize the logistics of individual road transport could save 70 to 190 million metric tons of carbon dioxide emissions by 2020 in the U.S. (GeSI, 2008). However, there is limited research and inconclusive evidence on the impacts of ridesourcing services as measured by VMT, traffic congestion, and greenhouse gas emissions (Ngo, 2015).

As for the efficiency of passenger rides, several studies argued that ridesourcing was more efficient than taxi, with shorter waiting times due to the application of GPS and GIS technologies (Chen, 2015), and higher average occupancy of 1.8 passengers per ride (Rayle, Shaheen, Chan, Dai, & Cervero, 2014). Similar results have been found that passenger-based capacity utilization and mileage-based capacity utilization were both higher for UberX compared to taxis (Cramer & Krueger, 2016). The main limitation of this study was the exclusion of mileage and times drivers have to travel from the point of log-out to the end location which overestimates their capacity utilization rate. Opponents, however, argued that ridesourcing drivers were likely to deadhead (drive without passengers) in order to pick up passengers, thus increased vehicle miles travelled and pollution (Anderson D. N., 2004). Though because ridesourcing platforms offer drivers much more information about the location of passengers and use pricing incentives to balance driver supply and passenger demand in order to minimize average wait times, there should in theory be less cruising for passengers than with taxicabs. However, Henao

(2017) revealed a low percentage of efficient travels in ridesourcing services and an overall increase in VMT based on the trip data collected as a ridesourcing driver in Denver.

In addition, some researchers argue that ridesourcing might replace some private automobile use, but also induce travel as well (Rayle et al., 2016). Compared to typical trip makers, ridesourcing users have been show to generate more trips with shorter lengths (Chen, 2015). UC Davis's report (Clewlow & Kulieke, 2017) concluded that ridesourcing was likely to contribute to the VMT growth in the major cities based on their nation-wide survey, but in net they conclude that the VMT changes were unknown. A detailed analysis of New York City suggested that ridesourcing services accounted for the addition of 600 million miles of vehicular travel to the city's roadway network over the past three years, after accounting for declines of mileage in yellow cabs and personal vehicles (Schaller, 2017). To reduce the emissions associated with all of this travel, two approaches have been proposed: (1) reduce total miles traveled by reducing deadhead miles, and (2) reduce emissions per mile by promoting clean energy vehicles (Zafar, 2018).

2.5 Summary

Current research on ridesourcing services focus more on the characteristics of users, trip purposes, and impacts on travel behaviors. These studies use mostly aggregate data to illustrate the rapid adoption and growth of these services, and survey data at regional or national levels to examine travel behavior. However, the overall environmental impacts, either in internal combustion or electric car scenarios, are still unclear due to the lack of data on disaggregate travel time attributes, as well as a reliance on ad hoc analytical approaches that eschew clearly structured travel behavior/mode choice models. Differentiating distances driven by type of travel (driving with passengers, cruising for picking up passengers, etc.) is very important to measuring TNC's VMT, as it takes into account the full array of ridesourcing travel effects compared to driving and other modes (Henao & Marshall, 2017). Given this research gap, I used disaggregate trip data and a greenhouse gas emission calculator in concert to assess the environmental impacts of ridesourcing services in gasoline hybrid and electric vehicle scenarios in order to identify the potential benefits and costs of electrification in ridesourcing services.

3 The Conceptual Model and Methods

The conceptual model guiding this research is depicted in Figure 1. The impacts might increase or decrease, depending on two factors – one factor is the *vehicle miles per travelled (VMT)* and the other is the *fuel economy*, which is affected by the *speed*. Emission rates go up high when automobiles are running at low, highly-congested speeds (<20mph). Emissions from vehicle use could be broken down into two segments respectively: **"cruising"** and "**effective driving"**, both of which vary spatially and temporally.

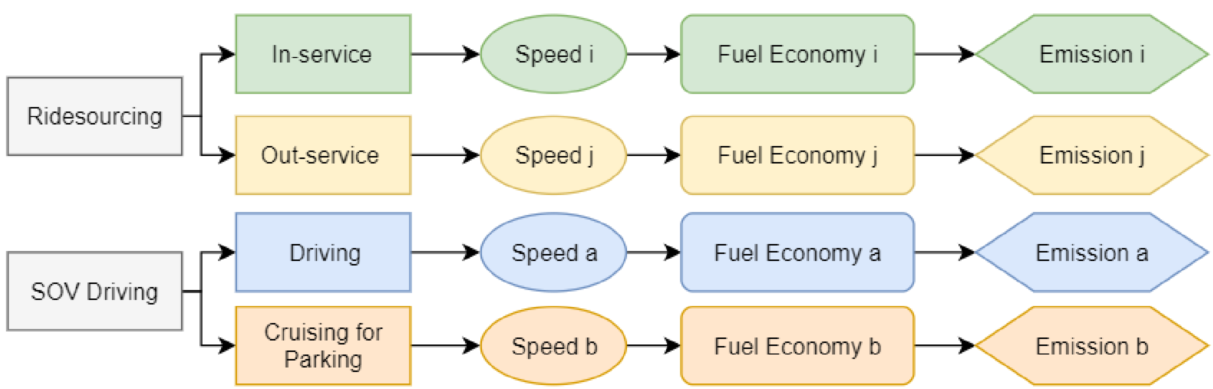

Figure 1 Conceptual Model

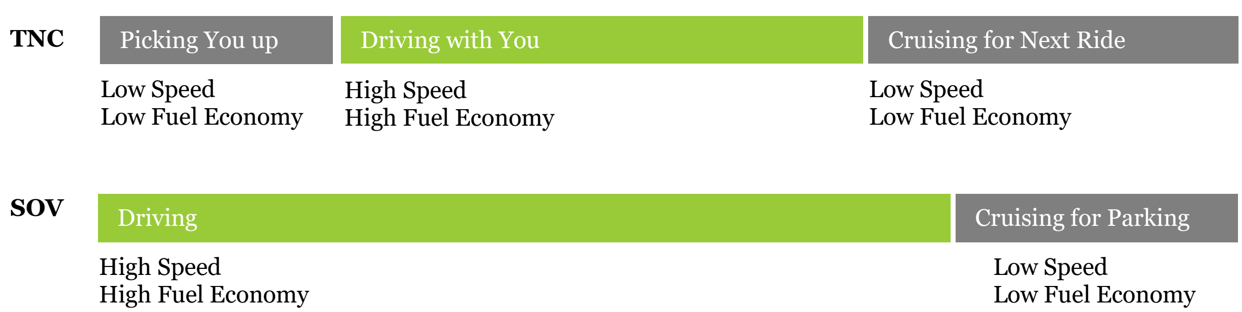

Figure 2 How Rides are Broken Down

For the Single Occupancy Vehicle Driving (SOV) scenario, effective driving is shown as the green bar in Figure 2, which is usually at the speeds (30-45 mph) that can achieve high economy. Cruising (the grey bar in Figure 2) is usually used for parking search. Congestion will add to the amount of time/distance for cruising for parking.

For the Ridesourcing (TNC) scenario, effective driving is when the driver is driving with passengers at high speeds that can achieve high fuel economy (green bar in Figure 2). Cruising, however, is more complicated for ridesourcing vehicles, which is comprised of two parts: (1) picking up passengers and (2) searching for new passengers (grey bar in Figure 2). In peak hours, there will be less cruising time/distance spent in searching for a passenger, but perhaps more time spent in picking up a passenger due to heavy congestion.

The model used in this research is highly simplified to emphasize the difference of "effective driving" and "cruising." In the real world, such dichotomy may not be as simple and clear as assumed in this research. For example, when passengers are carpooling in ridesourcing services with different origins and destinations, the driver may first drive with one passenger for some miles and then pick up another passenger. In this scenario, it is hard to clearly separate the distance of "effective driving" and "cruising." Besides, drivers are not always running at the same speeds in "effective driving" due to congestion. Furthermore, drivers may not always slowdown their speeds much when "cruising," if they easily find the passengers or parking spaces. I will address those complications in my next research, but not this one, due to limited time and data.

4 Data and Measurement

4.1 Environmental Impact Data

I assessed the environmental impacts of driving a private vehicle using *Alternative Fuel Lifecycle Environmental and Economic Transportation (AFLEET) Tool* [1]. In the Footprint Sheet of this tool, I input the amount of fuel consumption (including gasoline and electricity), the model year, and the U.S. state. The spreadsheet returned the amount of GHG emissions in short tons.

4.2 Travel Behavior Data

The environmental impacts (energy use and greenhouse emissions) are greatly affected by fuel economy, which varies by speed. Therefore, trips should be broken down into different segments according to running speeds. Although the changes of fuel economy by speed vary across different car models, as shown in Figure 4[2], they follow the same pattern depicted in Figure 3[3]. Fuel economy is predicted to go up as the speed increases until the fuel economy reaches the maximum level, at a speed of about 30 mph. Fuel economy will remain stable at the maximum level when speed change from 30 to 60 mph, then it will go back down as speed continues to increase. The fuel economy data are from the U.S. Department of Energy and the U.S. Environmental Protection Agency[4].

1 https://greet.es.anl.gov/afleet

2 https://blog.automatic.com/the-cost-of-speeding-save-a-little-time-spend-a-lot-of-money-5e8129899fec

3 www.fueleconomy.gov

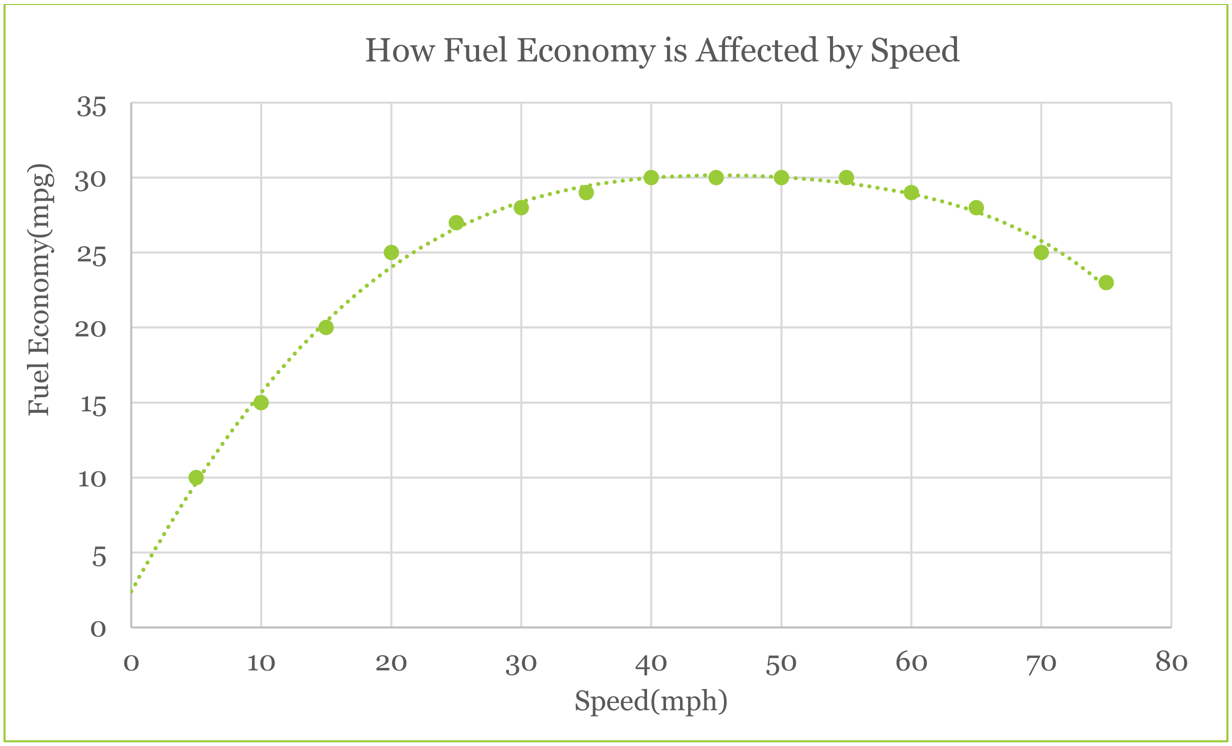

Figure 3 The Relationship between Fuel Economy and Speeds

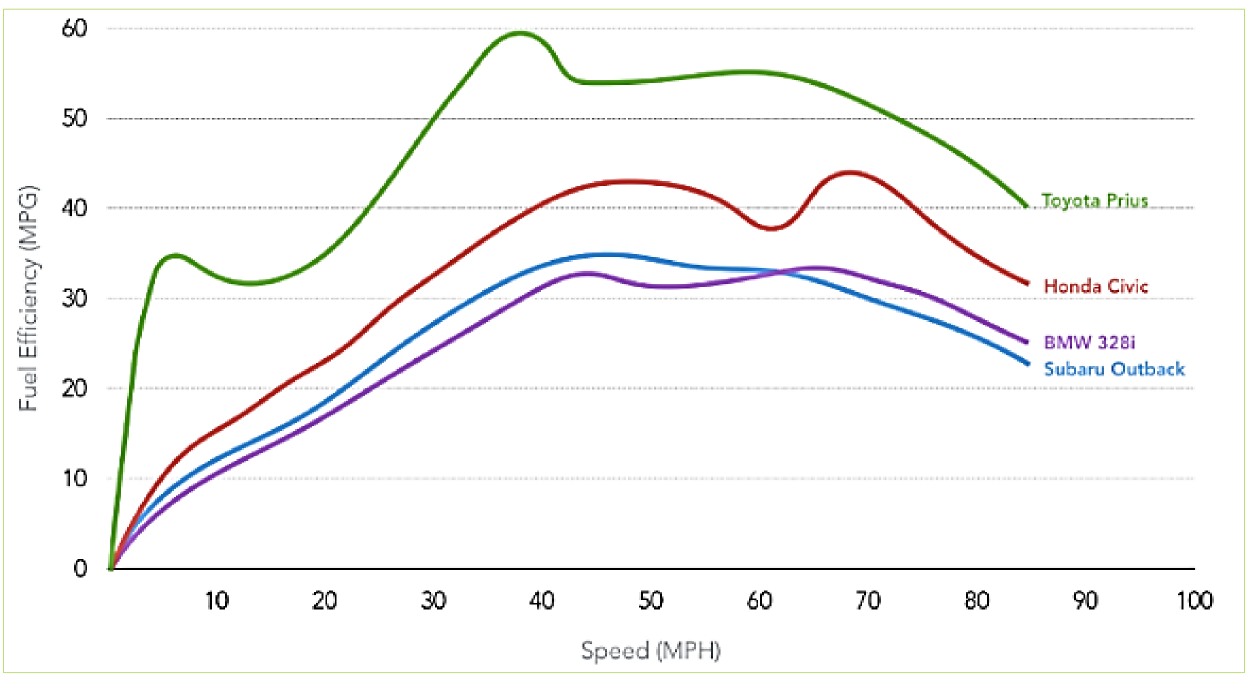

Figure 4 The Relationship between Fuel Economy and Speeds for Different Models

4 www.fueleconomy.gov

Table 1 Trip Model

	SOV (Single Occupancy Vehicles)		**TNC** (Ridesourcing Vehicles)	
Annual VMT (miles/year)	12400		12400 * (1+ the rate of induced trips)	
Trip Segments	Drive	Search Parking	In-service	Out-of-service
Trip Length Share %	97%	3%	78%	22%
Speed (miles/hour)	10.4	5.0	10.4	10.9
Fuel Economy (miles/gallon)	16.1	9.7	16.1	16.7

For a regular passenger sedan, I assumed that the annual total mileage is 12,400 miles based on AFLEET's assumption. Table 1 shows the trip model, as well as the data used in each model. A key to this research is to acquire reliable data on the percentage of travel distances based on speed (or fuel economy) for SOV driving and Ridesourcing.

In Ridesourcing mode, trips can be divided into *in-service* trips (driving with a passenger) and *out-of-service* trips (driving without a passenger and picking up passengers). The share of each kind of trip segment has been roughly estimated by San Francisco County Transportation Authority (SFCTA) in the report *TNCs Today: A Profile of San Francisco Transportation Network Company Activity,* based on ridesourcing trip data in San Francisco from mid-November to mid-December of 2016[1]. Approximately 21 percent of total ridesourcing VMT are out-of-service miles on weekdays, 19 percent on Saturdays, and 22 percent on Sundays. However, the report does not indicate how the shares of in-service and out-of-service travel fluctuated by hour of the day. In response to my request,

[1] https://www.sfcta.org/tncstoday

SFCTA staff generously agreed to share the datasets with me that include information of the average time and distance of in-service and out-of-service trips by hour in a month.

In single-occupancy-vehicle (SOV) mode, trips can be broken down into *driving* and *cruising for parking*. Currently, there are no data showing how much cruising for parking takes up in a typical SOV trip, which varies temporally and spatially from situations where parking is free and plentiful, to where it is scarce and expensive. It is difficult to collect such data due to the limited use of tracking devices. To address this problem, I used the aggregate annual data from INRIX Research's 2017 report on parking in San Francisco; it shows that people spent about 83 hours per year on searching for parking spaces in San Francisco (Cookson & Pishue, 2017).

4.3 Limitations of Data and Methods

The environmental effects of ridesourcing are uncertain, and indeed uncertainty – due to the lack and variation of the data – proved the biggest challenge in this research. Given this, average and range estimates were all that was possible. The uncertainty mainly comes from the ways to get and process data. The trip data from San Francisco County Transportation Authority (SFCTA) are not actual trip data from Transportation Network Companies like Uber and Lyft, but simulation data requested by Application Programming Interface (APIs), which do not represent observation of actual ridesourcing trips. Trips and pre-trips are imputed based on the changes in the supply of Uber and Lyft vehicles as revealed by each company's API. Some of the pickup locations and drop-off locations are not true trip origins and trip destinations. Instead, they represent where drivers accept rides (which are assumed to be a few minutes from true trip origins) and where drivers are available again (which are assumed to be near true trip destinations). Furthermore, no information on the specific ridesourcing products used (such as UberX or LyftLine) or vehicle occupancy can be derived from the data stream, which makes it difficult for me to calculate the results in the unit of per passenger miles traveled (PMT). Besides, these estimates from SFCTA were only a lower bound on ridesourcing trips in San Francisco, as all trips with one or more end outside the city (regional and through trips) were excluded from the analysis. The dataset only covered one month in 2016, which may not reflect the variations across the whole year period. Finally, San Francisco is unique for an American city not only for being an early adopter of ridesourcing, but for having a compact urban form that likely makes for (relatively) short vehicle trips and slow travel speeds. This implies limited applicability to a national context. These limitations will be addressed in my future studies when the real trip data from TNCs is available.

Furthermore, the analysis does not take the revenue of TNC drivers into account, but only focuses on the costs borne by TNC drivers, which cannot truly reflect the real incentives for drivers to choose among gasoline, hybrid, or electric vehicles. Following this track, the relationship between the price and the demand of TNCs should also be considered, which greatly affects the level of congestion and the level of induced trips.

5 Findings

5.1 The Fluctuating Efficiency of Ridesourcing Services

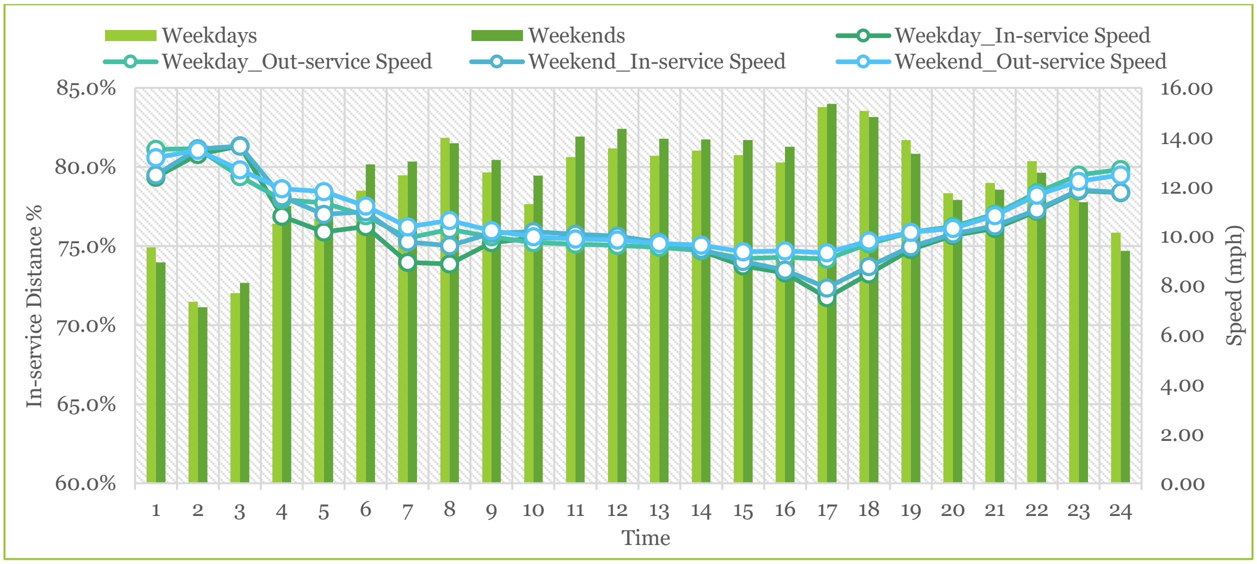

Figure 5 The Fluctuated Efficiency of Ridesourcing Services

Figure 5 shows how the efficiency of ridesourcing services fluctuated hourly in a single weekday and weekend day. The efficiency can be illustrated in two forms: (1) the percentage of in-service trip distance, and (2) the driving speed. The higher in-service trip distance percentage and speeds are, the more efficient the ridesourcing services are.

The first important finding is the relationship between the percentage of in-service travel distances to total travel distances and driving speeds. In general, when the ratio of in-service travel to total travel increases, speeds decrease. This phenomenon usually happens during 7 am-9 am, 11 am-1 pm and 5 pm-7 pm, when many people are requesting ridesourcing services to travel to work, lunch, and back home. Traffic is usually heavy during these time periods, and congestion slows down the ridesourcing vehicles. But ridesourcing vehicles also contribute to the congestion during peak hours. However, during another period when many people demand ridesourcing services, between 9 pm and 11 pm, the speeds are relatively higher than other peak times, since traffic congestion is much less than in commuting hours.

Another important finding relates to the comparison between weekday and weekend scenarios. Generally, ridesourcing services are less efficient on weekdays, taking speeds and the percentage of in-service travel distances into account. During weekdays, ridesourcing vehicles run at slower speeds than on weekends, especially during peak hours (7 am-9 am and 5pm -7 pm). The percentage of in-service travel distance to total travel distance is also lower in weekdays than weekends. This fact might indicate that people are more likely to use ridesourcing services for recreation on weekends but use their own vehicles for work on weekdays.

In addition, in-service speeds are usually lower than out-of-service speeds, especially during peak hours on weekdays. This fact suggests that drivers tend to drive faster to pick up passengers or wait for the next trip request, which, surprisingly, runs counter to my hypothesis. Another possible scenario might be that when ridesourcing vehicles operate with passengers, they usually travel in busy districts in urban areas. But when they are out-of-service, they may be more likely to travel on less congested roadways.

5.2 The Impacts of Induced Trips in Ridesourcing Services

With ridesourcing services, people are more likely to travel when it is not convenient for them to drive, like after drinking or to places with limited and/or expensive parking. As noted above, previous studies argued that ridesourcing might replace private automobile use but also induce travel (Rayle et al., 2016; Chen, 2015; Clewlow & Kulieke, 2017).

Since the number of induced trips is unknown and likely to differ spatially and temporally, I set the rate of induced trips to range from 0 to 100 percent, and then checked to see how greenhouse gas (GHG) emissions of ridesourcing and private vehicles varied with respect to the rate of induced trips. I also explores the possibilities in three scenarios with different percentages of in-service travel distances to total travel distances. Table 2 shows the assumptions and parameters used in each scenario.

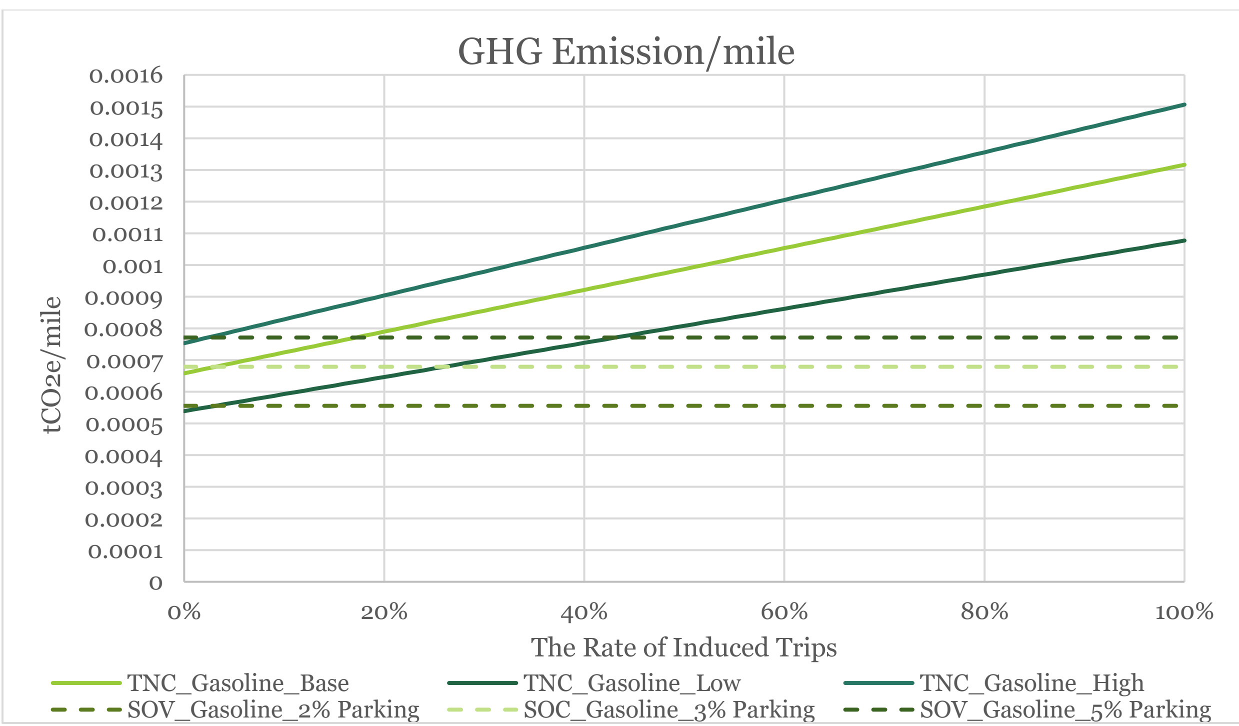

Figure 6 The GHG Emissions of TNC and SOV

Table 2 Assumptions of Different Scenarios Based on Percentage of In-service Travel

	SOV (Single Occupancy Vehicles)		**TNC** (Ridesourcing Vehicles)	
Annual VMT (miles/yr)	12400		12400 * (1+ the rate of induced trips)	
Trip Segments	**Drive**	**Search Parking**	**In-service**	**Out-of-service**
Base Model (Average percentage of effective driving)				
Trip Length Share %	97%	3%	78%	22%
Speed (miles/hour)	10.4	5.0	10.4	10.9
Fuel Economy (miles/gallon)	16.1	9.7	16.1	16.7
Low Model (Low percentage of effective driving)				
Trip Length Share %	95%	5%	67%	33%
Speed (miles/hour)	14.7	5.0	14.7	13.3
Fuel Economy (miles/gallon)	20.2	9.7	20.2	19.0
High Model (High percentage of effective driving)				
Trip Length Share %	98%	2%	85%	15%
Speed (miles/hour)	8.5	5.0	8.5	9.9
Fuel Economy (miles/gallon)	14.0	9.7	14.0	15.5

Figure 6 shows how GHG emissions change with the induced trip rate of ridesourcing services. The point where TNC and SOV intercepts is defined as the "green point." Beyond this point, TNCs are assumed to generate more emissions than SOV travel.

If I assume in the Base Model (where ridesourcing vehicles have an average percentage of effective driving, namely 78%) that private vehicles spend about 5 percent of their total mileage searching for parking, this amounts to about 20 minutes per day at a speed of 5 miles per hour; under such circumstances, ridesourcing services will generate fewer GHG emissions as long as the assumed levels of induced trips does not exceed 20 percent. When the distance traveled for parking is about 3 percent, which is about 13 minutes per day, TNCs quickly reach the "green point" at a level of induced trips of 5 percent. When the distance traveled for parking is 2 percent, which is about 8 minutes per day, under no circumstances will TNCs generate fewer GHG emissions than SOVs.

When TNCs are assumed to operate with a high percentage of in-service travel distances to total travel distances (85%), it will reach the “green point” even when the distance traveled for parking is as high as 5 percent. This indicates that when TNCs run in peak hours, they will not generate fewer emissions than SOVs even with low levels of induced trips. On the contrary, if the TNC operates with a low percentage of in-service travel distances to total travel distances (67%), the “green point” can be as far as 25 percent when the distance traveled for parking search is 3 percent, and as 45 percent when the distance traveled for parking search is 5 percent. Therefore, driving speeds likely play an important role in determining the magnitude of TNCs’ GHG emissions compared to SOVs’. Congestion, partly contributed by TNC vehicles, though mostly caused by private vehicles, appears to be the bottleneck that prevents TNCs from generating fewer emissions than SOVs. For SOVs, distance traveled for parking search is a particularly important factor affecting GHG emissions. Within the “green point,” the environmental impacts of TNCs vis-à-vis SOVs are likely shaped by parking availability. But such benefits will be offset if TNCs induce large numbers of new trips.

The results above are suggestive, but not conclusive since they are sensitive to different inputs. The goal is to provide an exploratory framework to quantify the influence of induced trips, the percentage of in-service travel and the congestion on the environmental impacts of ridesourcing services. In addition, while searching for parking is purely a cost, induced trips can benefit society by enabling economic transactions and social interactions. A high level of induced trips may indicate the high level of convenience of TNCs that meet people’s needs. The way to reduce TNC’s greenhouse gas emissions might not be controlling the level of induced trips since it varies spatially and temporally in market. A more realistic way might be using cleaner vehicles like hybrids and electric vehicles. This leads to the analysis in the next section.

5.3 Using Clean Energy Vehicles to Reduce GHG Emissions

The above analysis indicates that, given the parameters of my simplified behavioral model, there is limited opportunities for TNCs to reduce the GHG emissions compared to SOV travel if TNC drivers use conventional gasoline-powered cars. In fact, the overall vehicle fleet is shifting toward cleaner vehicles like hybrid vehicles (HVs) and electric vehicles (EVs) that emit fewer GHGs. There is evidence that this transition is moving fast among ridesourcing vehicles due to a short payback period than private vehicles (Zafar, 2018). The data on taxi fleet vehicles reveals a recent transition to high mileage, low-polluting taxi fleets over the last 10 years. New York City, Boston, Los Angeles, and San Francisco all issued local mandates and incentives encouraging the shift to hybrid vehicles (Wagner, 2018). Ridesourcing services, however, do not need to adhere to fleet economy mandate nor do they qualify for fleet vehicle incentive programs, and their programs focus more on electric vehicles rather than hybrid vehicles. For example, Uber's first U.S.-based electric vehicle program launched in Portland, Oregon in April 2017. The company has also run EV pilots in Lisbon, Madrid, Johannesburg, and Paris. There is a concern that if Uber and other mobility companies don't move into vehicle electrification, autonomous and shared vehicles could actually worsen carbon pollution by making personal vehicle travel easier (Pyper, 2017). Similarly, Lyft also aims to provide one billion rides per year using electric autonomous vehicles by 2025, together with a goal to reduce CO_2 emissions across the U.S. transportation sector by at minimum 5 million tons annually (Etherington, 2017). These programs aim to increase the application of EVs considering that Uber has the technology platform to better maximize the use of cars and shorten the payback period than a typical passenger car that sits idle 96 percent of the time (John & Logan, 2017). Considering the urgent needs for and the current trends of TNC electrification, I examined how hybrid and electric vehicles can help reduce the GHG emissions of TNC vehicles by calculating the amount of GHG reduction and the cost of shifting from gasoline cars to clean energy cars. Given the wide variations in fuel prices, electricity prices, and the energy sources used for electricity production, I also considered the spatial variations of various scenarios across states in the U.S. using ArcGIS software.

5.3.1 The Cost and Effectiveness of Clean Energy Vehicles

Figures 7 and 8 show the curves of GHG emissions and the unit cost per VMT. The cost is the total Net Present Value (NPV) of vehicle purchase, maintenance, fuel consumption and vehicle resale during a 10-year vehicle ownership. My calculation was based on the assumption that in-service travel distances takes up 78% of the total travel distances for ridesourcing vehicles.

As for the reduction in GHG emissions (see Figure 7), hybrid vehicles (HVs) and electric vehicles (EVs) are both estimated to contribute greatly to GHG emission reductions. Hybrid vehicles will significantly move the “green point” to 43 percent, which means that with hybrid vehicles, TNCs will not generate more GHG emissions than gasoline private cars when the level of induced trips is lower than 43 percent. Electric vehicles, however, can always emit fewer GHG emission than gasoline private vehicles. Higher fuel economy and cleaner energy can not only help reduce GHG emissions when no induced trips happen, but also slow down the emission growth as the level of induced trips goes up.

As for the cost of shifting from gasoline vehicles to cleaner vehicles for TNC drivers (see Figure 8), if the revenue is not considered, TNCs with gasoline vehicles will quickly become more expensive than SOVs as the level of induced trips rise. Here, I defined the point where SOV and TNC intersect as the “economical point”, the value of which is the level of induced trips. When the cost of TNC is lower than the cost of SOV, TNC is considered more economical than SOV. Hybrid vehicles will cost less for TNC drivers no matter what the level of induced trips is. But the reduction of cost is limited, only moving the “economical point” a little bit farther about 10 percent, which means that hybrid vehicles allow TNC drivers to have 10 percent more induced trips than gasoline vehicles do to generate less GHG emissions than SOVs. Electric vehicles, by contrast, are always more costly than gasoline vehicles for TNC drivers whatever the level of induced trips is, so there is no “economical point.” Costs are projected to increase as the level of induced trips increases, but not as fast as hybrid or gasoline vehicles. When the level of induced trip reaches 80 percent, electric vehicles will become more economical for TNC drivers than gasoline vehicles. However, the cost will jump up again as the level of induced trips goes up to 90 percent when a battery replacement is required. The battery life assumed in this analysis is 120,000 miles. Therefore, hybrid vehicles appear to be the least costly choice compared to electric vehicles and gasoline vehicles.

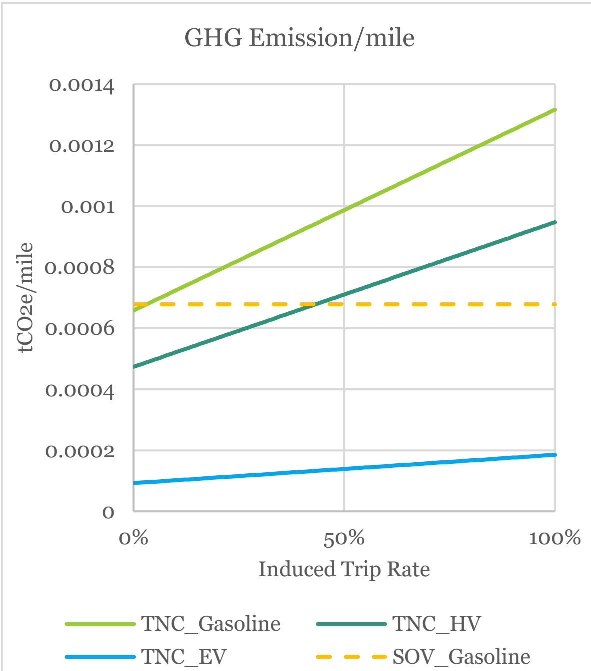

Figure 7 How Clean Energy Vehicles Save GHG Emissions

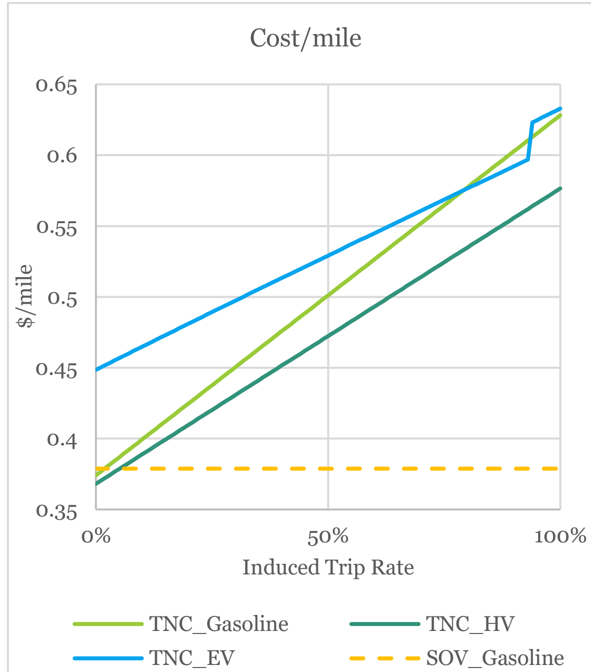

Figure 8 The Cost of Using Clean Energy Vehicles

5.3.2 The Sensitivity Analysis of Cost-Effectiveness

In order to assess the trade-offs between the additional cost of shifting from gasoline-powered cars to electric vehicles and such transitions will affect GHGs, I defined the concept of cost-effectiveness as follows:

$$Cost - Effectiveness = \frac{(Cost\ of\ HVs\ or\ EVs - Cost\ of\ Gasoline\ Vehicles)}{(GHG\ of\ Gasoline\ Vehicles - GHG\ of\ HVs\ or\ EVs)}$$

As an effort to determine the most influential factor affecting the cost-effectiveness of shifting from gasoline vehicles to hybrid and electric vehicles in ridesourcing sector, I carried out a sensitivity analysis to determine the significance of various factors. The factors are: (1) ***Fuel Economy*** of hybrid and electric vehicles, (2) ***Vehicle Price*** of hybrid and electric vehicles, (3) ***Vehicle Resale Price*** of hybrid and electric vehicles,

(4) ***Maintenance Price*** of hybrid and electric vehicles, and (5) ***Fuel Price*** of hybrid and electric vehicles. In each scenario, the value of each factor is decreased or increased by 10 percent with other factors held constant. All the base values for gasoline cars are kept constant in all cases. The level of induced trips was set to be zero percent in this sensitivity analysis. The results are shown in Figure 9 for hybrid vehicles and Figure 10 for electric vehicles. The x-axis represents the percentage of changes compared to the original base model.

The sensitivity analysis shows that the most influential factor in affecting the cost-effectiveness is the vehicle purchase price for both hybrid and electric vehicles. Fuel price and maintenance costs are the next most influential factors, with maintenance cost more sensitive for electric vehicles, and fuel price more sensitive to hybrid vehicles. Fuel economy and resale price are not as influential as these other factors, especially for hybrid vehicles. These results indicate that to encourage ridesourcing drivers to use clean energy vehicles – either hybrid or electric vehicles – the most effective path would be to decrease the price of vehicles through tax credits or subsidies. For hybrid vehicles, subsidies for maintenance and fuel would also be effective. For electric vehicles, efforts to increase fuel economy and decrease maintenance fee and fuel price would also work well.

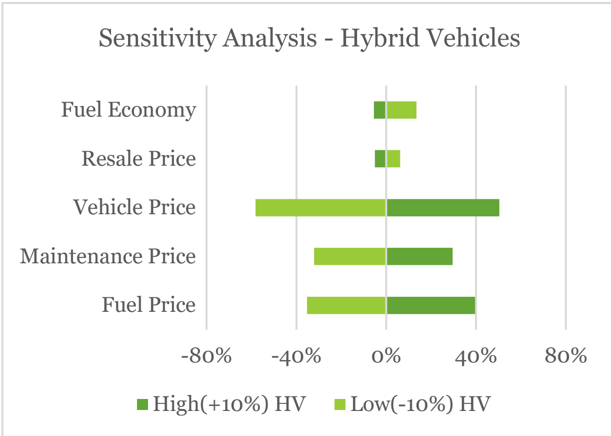

Figure 9 Sensitivity Analysis - Hybrid Vehicles

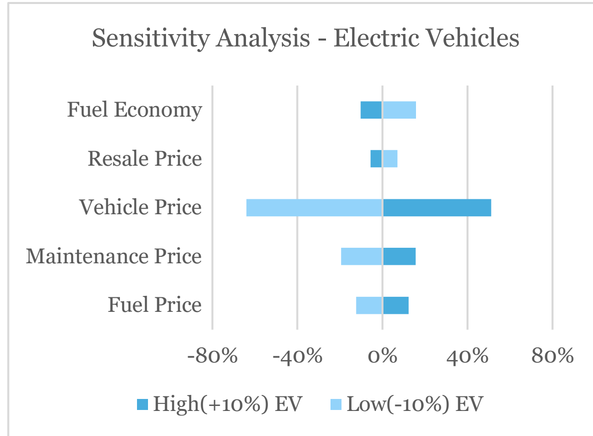

Figure 10 Sensitivity Analysis -Electric Vehicles

5.3.3 The readiness for electrification varies by state

The analysis above is based in the context of San Francisco, California, where the gas price is $3.03/gal, electricity price is $0.19/kwh, and the share of clean energy used for electricity production is 99.4 percent. Given the variations in gas price, electricity price, energy structure, charging availability, and regulations, I investigate spatial variation among U.S. states using ArcGIS software in this section. The data is classified by quantile.

(1) The cost-effectiveness of hybrid vehicles

The cost-effectiveness is negative in most states, which means that shifting to hybrid vehicles will be both economical (fewer costs) and environmental-friendly (fewer GHG emissions) for both SOV and TNC drivers (see Figure 11). Generally, states in the western and north-east parts of the U.S. offer higher levels of cost-effectiveness for hybrid vehicle purchases, while states in the mid-south are not as ideal as other states because higher shares of electricity are generated from fuel oil and coal. California, Hawaii, Washington, and Alaska are the top four states that offer drivers the least financial incentives to shift to hybrid vehicles mainly because of the high fuel price.

(2) The cost-effectiveness of electric vehicles

Compared with hybrid vehicles, electric vehicles are projected to greatly decrease the amount of greenhouse gas emissions, but with very high additional cost. Therefore, the cost-effectiveness of shifting from gasoline vehicles to electric vehicles is always positive (see Figure 12). The spatial distribution pattern of cost-effectiveness is generally similar with that of hybrid vehicles in spite of some differences in the middle part of the U.S. States in the west and north-east offer the strongest financial incentives and the greatest environmental benefit from a shift to electric vehicles, because electricity costs are low and the projected reductions in greenhouse gas emissions are high. However, the cost-effectiveness of shifting to electric vehicles in mid-north states is lower than that of mid-south states.

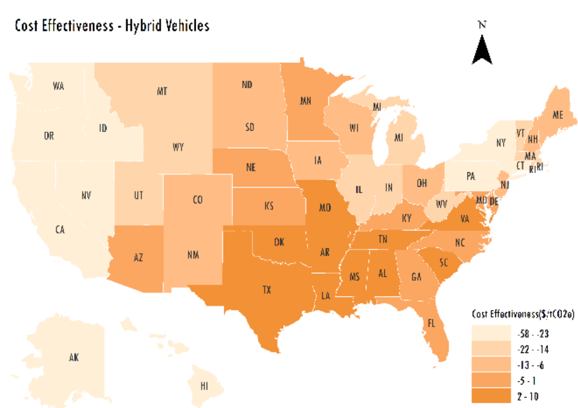

Figure 11 The Cost-effectiveness of Shifting to Hybrid Vehicles

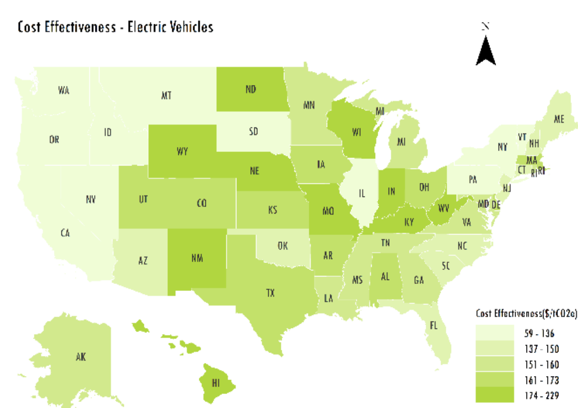

Figure 12 The Cost-effectiveness of Shifting to Electric Vehicles

(3) The fuel price index

Here, I defined "fuel price index" as the ratio of electricity price to gasoline price, which indicates how economical the electricity is compared to gasoline.

$$Fuel\ Price\ Index = \frac{Electricity\ Price}{Gas\ Price}$$

States with a high fuel price index generally concentrate geographically in three clusters: south-west, mid-north, and north-east, which indicates that relatively high electricity prices present barriers to electric vehicle purchases in these areas (see Figure 13).

(4) The share of clean energy used for electricity production

Clean energy used for electricity production includes natural gas, nuclear, hydrogen, wind, biomass, solar, and geothermal. Here, coal and oil are considered as unclean. The definition is shown as follows:

$$Clean\ Engergy\ Share = \frac{1 - Percentage\ of\ Coal\ and\ Oil}{Percentage\ of\ Coal\ and\ Oil}$$

The clean energy share suggests the level of environmental benefits to use electric vehicles. If the electricity production relies heavily on coal or oil (with low clean energy share), the environmental benefits of promoting the adoption of electric vehicles is considerably diminished. States in the west and north-east generate a large share of their electricity from clean energy sources: over 60 percent. When we combine the distribution of clean energy share and fuel price index, we can find that states can be roughly divided into three groups (see Table 3). The level of cost-effectiveness can be indicated by the ratio of fuel price index to clean energy share. States with high fuel price index and low clean energy share, like California and New York, usually have low EV cost-effectiveness. Mid-southern states like North Dakoda cost more to reduce greenhouse gas emissions via electric vehicles due to relatively high electricity price and low share of clean energy sources to produce electricity. States in mid-south and south-east, however, are at the medium levels of fuel price, clean energy and cost-effectiveness (see Figure 13 and Figure 14).

Table 3 Regional Division for the Cost-effectiveness of Electric Vehicles

Region(s)	Fuel Price Index	Clean Energy Share	EV Cost-effectiveness	Examples
South-west & North-east	High	High	Low	California, New York
Mid-north	High	Low	High	North Dakoda
Mid-south & South-east	Medium	Medium	Medium	Texas, Florida

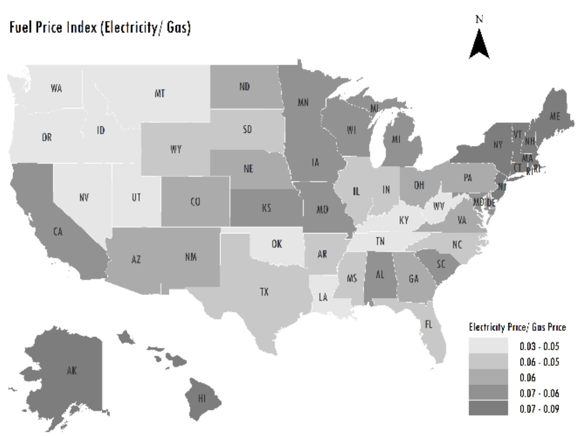

Figure 13 The Spatial Distribution of Fuel Price Index

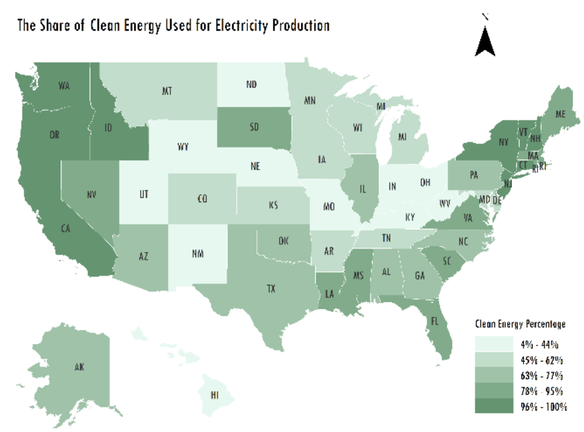

Figure 14 The Spatial Distribution of Clean Energy Share

(5) Charging Availability

I used the number of charging outlets to measure the charging availability by state[1]. Generally, states along the west and east coasts have higher charging availability (see Figure 15). Some states in the middle of the U.S., like Texas, Colorado, and Missouri, also have high charging availability. Charging availability, though not counted as the direct cost in this analysis, is a very important factor that might affect the popularity of electric vehicles. Higher availability indicates higher level of easiness to shift from gasoline cars to electric vehicles.

(6) Regulatory Incentives

Forty-five states and the District of Columbia currently have various incentives for hybrid and electric vehicles, which can range from tax credits or rebates to fleet acquisition goals or exemptions from emission testing[2]. I categorized the incentives into seven types based on the methods from National Conference of State Legislature and Plug-in America: Purchase, HOV Access, Charging, Licensing, Parking, Infrastructure and Insurance (see Table 4). The level of incentive variety is measured by the number of incentive categories issued in each state. California, Colorado, Florida, Georgia, Maryland, New Jersey, New York, and North Dakota have provided incentives in the areas of purchase, HOV access, charging, licensing, parking, infrastructure and insurance. Again, states along the west

[1] Data source: https://www.afdc.energy.gov/fuels/stations_counts.html

[2] Data sources: http://www.ncsl.org/research/energy/state-electric-vehicle-incentives-state-chart.aspx; https://www.afdc.energy.gov/laws/state; https://pluginamerica.org/why-go-plug-in/state-federal-incentives/

and east coasts have made greater efforts to promote the hybrid and electric vehicle adoption, while states in the middle of the U.S., especially those located along the diagonal line running from Montana to Mississippi, have adopted fewer than three kinds of incentives. Table 4 and Figure 16 shows the geographic distribution of each kind of incentive among U.S. states. The most widely adopted incentive is the insurance discount, with 90 percent of the states offering insurance discounts for drivers, followed by licensing (84% of the states) and charging discounts (78% of the states).

Table 4 Regulatory Incentive Coverage

Incentive Category	Incentive Contents	The percentage of states providing this incentive
Purchase	Financial incentives such as rebates, sales tax exemptions and tax credits on the purchase or lease of a PEV, or a conversion to a PEV.	47%
HOV Access	Access to the carpool/high-occupancy-vehicle lane may be allowed for some PEVs with the right decal displayed.	29%
Charging	Utilities may offer certain EV charging rates or offer low or reduced rates at night for EVs	78%
Licensing	Incentives such as registration discounts and emission testing exemption	84%
Parking	Commercial and public buildings, cities and towns that may offer free or discounted parking for PEVs	55%
Infrastructure	Rebates and tax credits available on electric vehicle supply equipment (EVSE) for residences, multi-family buildings and businesses.	61%
Insurance	Insurance discounts for PEV drivers.	90%

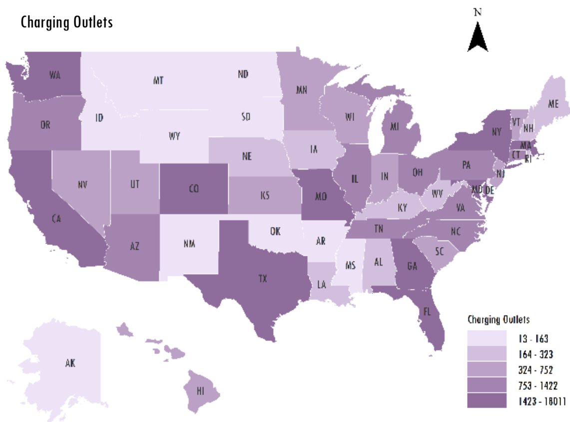

Figure 15 The Spatial Distribution of Charging Outlets

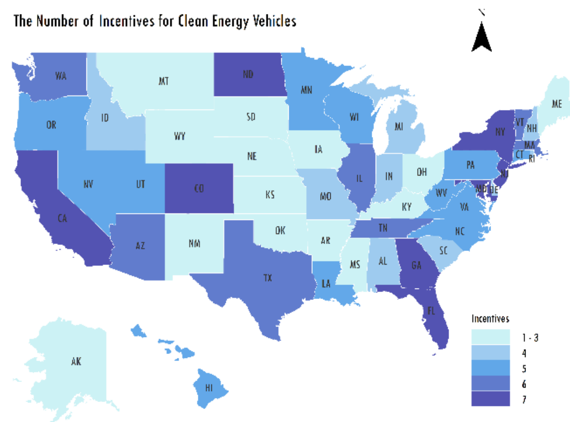

Figure 16 The Spatial Distribution of Incentives

(7) Cumulative readiness for ridesourcing electrification

In order to determine which states are best positioned to motivate ridesourcing drivers to shift from gasoline to hybrid or electric vehicles, I drew the map below to show the cumulative or comprehensive readiness, which combines all the factors: cost-effectiveness of hybrid vehicles and electric vehicles, fuel price index, clean energy share, charging availability and regulatory incentive. For each factor, data is normalized within the range from 0 to 1.

$$x_i' = (x_i - x_{min})/(x_{max} - x_{min})$$

Where,

x_i is the original value of state i, x_i' is the normalized value of state i

x_{min} is the minimum value of the states, x_{max} is the maximum value of all the states

The comprehensive readiness can be calculated by the formula as follow:

$$Readines = -(EV\ Cost\ Effectiveness + HV\ Cost\ Effectiveness + Fuel\ Price\ Index) + (Clean\ Energy\ Share + Charing\ Availability + Regulatory\ Incentive$$

Where three factors impose positive effects (clean energy share, charging availability and regulatory incentive), and the other three (HV cost-effectiveness, EV cost-effectiveness and fuel price index) exert negative effects. I classified the results into five levels by equal interval: Very Low (<-1), Low (-1~0), Medium (0~1), High (1~2) and Very High (>2) (see Figure 17). In general, states in the west provide high readiness for ridesourcing electrification. California is in the first tier, followed by Washington and Oregon in the second tier. States in the third tier are concentrated in four areas: Idaho and Nevada in the mid-west, Illinois in the middle, Georgia and Florida in the south, as well as six states (Pennsylvania, New Jersey, New York, Vermont, Cincinnati, and Rhode Island) in the east. States in the middle part generally have low readiness for electrification.

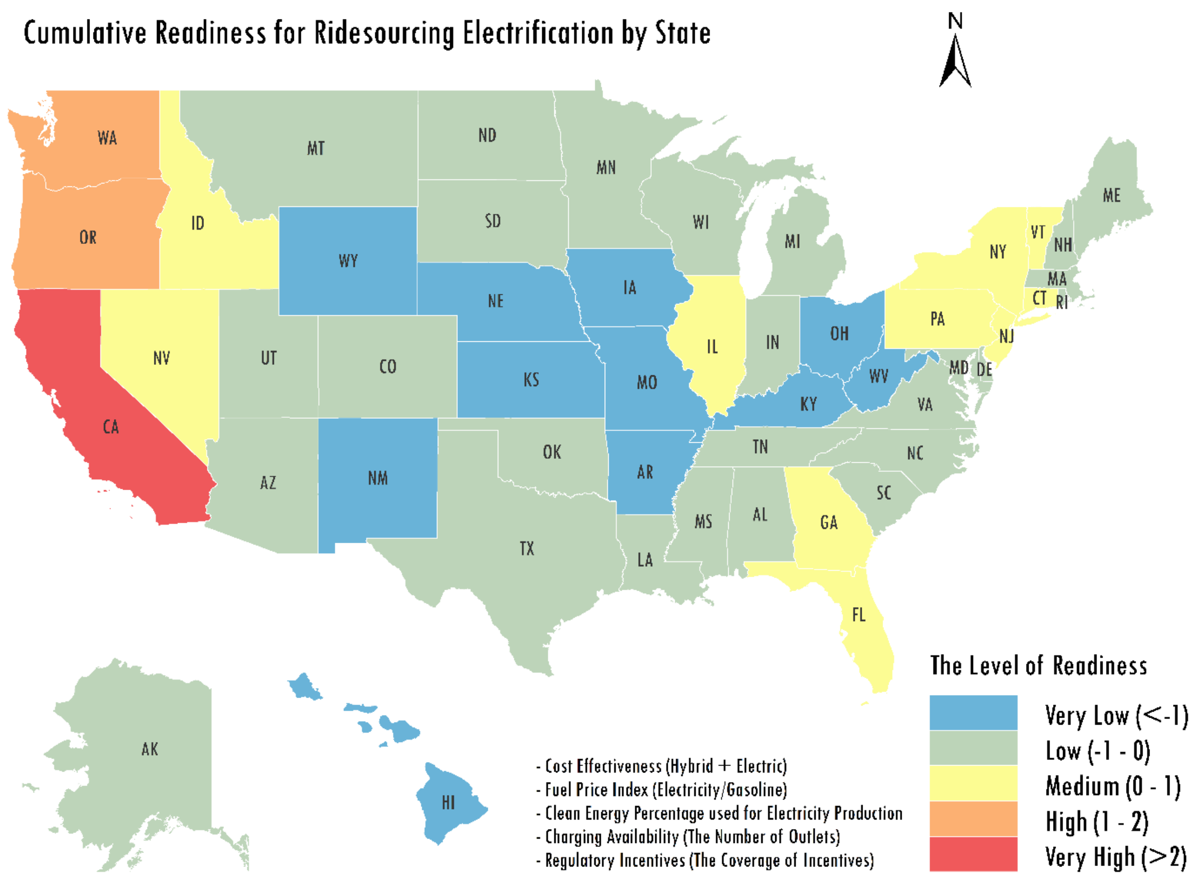

Figure 17 Cumulative Readiness for Ridesourcing Electrification by State

6 Conclusion

The assessment of greenhouse gas emissions for ridesourcing services (TNC) and single-occupancy driving (SOV) indicates that several factors determine whether ridesourcing services can produce less greenhouse gas emissions: the level of induced trips, the percentage of in-service travel distances to total travel distances in ridesourcing, driving speeds, and the amount of driving devoted to searching for parking. The "green point," or the percentage of induced trips at which TNC emissions start to exceed SOV emissions given the assumption that there is no induced trips among SOVs, can range from 5 percent (85% TNC in-service trip, 8.5 mph traveling, and 2% distance for SOV parking search) to 40 percent (67% TNC in-service trip, 14.7 mph traveling, and 5% distance for SOV parking search). Congestion, partly contributed by TNC vehicles, but mostly contributed by SOVs, is the bottleneck that prevents TNC from being green on roads.

Considering the fact that TNCs have limited opportunities to reduce the GHG emissions vis-à-vis SOVs with gasoline vehicles, I examined the possibility of increasing the share of hybrid or electric vehicles in the Ridesourcing fleet. As for GHG emissions, hybrid vehicles (HVs) and electric vehicles (EVs) are both projected to contribute significantly to emissions reductions. Hybrid vehicles will significantly move the "green point" to 43 percent, which means that with hybrid vehicles, TNCs will not generate more GHG emissions than gasoline private cars when the level of induced trips is lower than 43 percent. Electric vehicles, however, can always generate fewer GHG emissions than gasoline private vehicles. Higher fuel economy and cleaner energy can not only help reduce the amount of GHG emissions when there are no induced trips, but also slow down the GHG growth as the level of induced trips goes up. As for the cost, if we do not consider the revenue of TNC drivers, driving with gasoline vehicles will quickly become more expensive than SOV as the rate of induced trips rate goes up. Hybrid vehicles will cost less for TNC drivers no matter what the level of induced trips is. Electric vehicles, by contrast, are always more costly than gasoline vehicles for TNC drivers whatever the level of induced trips is. When the rate of induced trips reaches 80 percent, electric vehicles are projected to become more economical than gasoline vehicles for TNC drivers. However, the cost will jump up again as the level of induced trips goes up to 90 percent when battery replacement is required.

I then conducted sensitivity analysis to determine the most influential factors affecting the cost-effectiveness of shifting from gasoline vehicles to hybrid and electric vehicles in ridesourcing sector. To encourage ridesourcing drivers to acquire and use cleaner energy cars, either hybrid or electric vehicles, the most effective way is to decrease the price of vehicles, likely via tax credits or subsidies. For hybrid vehicles, subsidies for maintenance and fuel would also be effective. For electric vehicles, the efforts to increase the fuel economy of electric vehicles, decrease maintenance costs and electricity rates would also work well.

I finally did a spatial analysis of comprehensive readiness for electrification using ArcGIS leveraging the data of cost-effectiveness, gas price, electricity price, energy structure, charging availability and regulatory incentives. The results are classified into five levels by quantile: Very Low, Low, Medium, High and Very High levels of electric vehicle readiness. States in the west offer high levels of readiness for ridesourcing electrification.

California is in the first tier, followed by Washington and Oregon in the second tier. States in the third tier are concentrated in four areas: Idaho and Nevada in the mid-west, Illinois in the middle, Georgia and Florida in the south, as well as six states (Pennsylvania, New Jersey, New York, Vermont, Cincinnati, and Rhode Island) in the east. States in the middle part generally have low readiness for electrification.

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